The effect of signal-temporal uncertainty on detection in bursts of noise or a random-frequency complex

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Abstract: This study examined the effect of signal-temporal uncertainty on detection of a 120-ms, 1-kHz tone in the presence of a continuous sequence of 120-ms bursts of either a broadband noise or a random-frequency, two-tone complex. Using the method of constant stimuli, signal-temporal uncertainty was defined as the difference in threshold across temporally uncertain and temporally defined listening conditions. Results indicted an average effect of signal-temporal uncertainty of 2 dB for the noise masker compared to 9 dB for the random-frequency, two-tone masker. These results suggest that signal-temporal uncertainty may be more detrimental for conditions in which informational masking dominates performance.

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1. Introduction

Multiple sources of acoustic uncertainty are encountered in natural environments. Relevant signals can occur at unpredictable times, and listeners do not always know what spectral and level information will be contained in the signals when they occur. In the laboratory, stimulus uncertainty is typically introduced by varying dimensions of the target signal, the background masker, or both. Large detrimental effects of stimulus uncertainty have been observed, particularly for masker-spectral uncertainty. In this context, masker-spectral uncertainty is produced by randomly varying the frequency components of a multi-tonal masker on each presentation. Compared to performance in quiet, masker-spectral uncertainty can elevate detection thresholds for a fixed-frequency tone by as much as 50 dB (e.g., Neff and Green, 1987). Moreover, substantial masking can occur in the absence of masker energy falling within a presumed auditory filter around the signal. The term "informational" masking is often used to distinguish these effects from peripherally based or "energetic" masking, although factors other than stimulus uncertainty can also produce substantial informational masking (reviewed by Durlach, 2006).

Several investigations have examined the masking produced by randomly varying the spectral content of a multi-tonal masker (e.g., Neff and Green, 1987; Kidd *et al.*, 1994), but effects of other types of uncertainty have received less investigation. Researchers have noted, however, that stimulus uncertainty in dimensions other than frequency and/or the combination of uncertainty across multiple dimensions can contribute additional detriments to subjects' performance (e.g., Durlach *et al.*, 2003). The purpose of the current study was to examine the effect of one potential contributor to informational masking, signal-temporal uncertainty, in the context of a multi-tonal informational masking paradigm.

Previous studies of pure-tone detection in quiet or in noise have found that subjects' performance improves when signals occur at expected versus unexpected times (e.g., Egan *et al.*, 1961; Chang and Viemeister, 1991). Furthermore, subjects are better able to focus attention on auditory events when they are predictable in time (reviewed by Jones and Yee, 1993). Nonetheless, the effect of signal-temporal uncertainty appears to be small for conditions in which energy-based masking dominates performance (e.g., Egan *et al.*, 1961; Watson and Nichols, 1976; Green and Weber, 1980). For example, Green and Weber (1980) varied the temporal position of a 1-kHz sinusoid in a sequence of ten, 50-ms bursts of broadband-noise. The effect of signal-temporal uncertainty was less than 2 dB.

In contrast to studies of tone-in-noise detection, the effect of signal-temporal uncertainty may be larger for conditions that produce substantial informational masking. Leibold and Werner (2006) examined infants' detection of a 1-kHz tone in the presence of repeating presentations of a random two-tone masker. Thresholds for adult control subjects were higher than previously reported for stimuli with similar spectral and level properties (e.g., Neff and Dethlefs, 1995). One explanation for the elevated thresholds reported by Leibold and Werner is that procedural modifications designed to facilitate infant testing increased signal-temporal uncertainty. In contrast to studies that have examined informational masking in adults using 2IFC or yes/no tasks in which the listening interval was defined, subjects did not have *a priori* knowledge regarding the onset of signals. Thus, subjects were listening under conditions of both masker-spectral and signal-temporal uncertainty.

Recent studies are consistent with the idea that the effect of signal-temporal uncertainty depends on the particular stimuli and procedures employed. Best *et al.* (2007) found that subjects could more accurately identify birdsong when provided with a visual cue defining the time interval that contained the target. However, a smaller improvement was observed for recalling digits presented in time-reversed speech. Best *et al.* suggested that the benefit of knowing when to listen depends on the salience of the stimuli and the listener's experience with them. In work related to their infant study, Leibold and Werner (2003) also suggest that the benefit of knowing when to listen is larger for conditions in which informational masking dominates performance. Detection thresholds for a 1-kHz tone were estimated in the presence of a random two-tone masker. The average threshold for five trained adults was 16 dB lower when the listening interval was defined by a visual cue compared to when the listening interval was uncertain. However, response bias was not accounted for with the single-interval adaptive procedure. Thus, it is difficult to determine whether this threshold difference reflects a difference in sensitivity or a difference in detection strategy.

Based on Leibold and Werner (2003), the current study examined whether the effect of signal-temporal uncertainty is larger for conditions that generate considerable informational masking. Using the method of constant stimuli, thresholds for a 120-ms, 1-kHz tone were computed from an unbiased estimate of sensitivity (d') in the presence of 120-ms bursts of either a broadband noise or a random-frequency, two-tone complex. For each masker, the effect of signal-temporal uncertainty was defined as the threshold difference across temporally uncertain and temporally defined conditions. The hypothesis was that the effect of signal-temporal uncertainty would be larger for the random two-tone masker, expected to produce substantial informational masking, than for the noise masker.

2. Method

2.1 Subjects

The subjects were four adults (21 to 27 years) with thresholds in quiet of $\leq$20 dB HL for octave frequencies from 0.25 to 8 kHz, bilaterally. Subjects were tested individually in a double-walled, sound-treated room for 2-h sessions, including regular breaks. All subjects had experience with both the task and stimuli and were selected because they exhibited substantial masking in the presence of random two-tone maskers. An additional subject was tested but excluded from analysis. Despite multiple test blocks, this subject's data remained variable and resulted in a poorly fitted psychometric function for one condition (r^2=0.4).

2.2 Stimuli and equipment

In all conditions, the signal was a 1-kHz pure tone of 120-ms total duration, including 5-ms, $\cos^2$ onset/offset ramps. There were two types of maskers: broadband noise (0.3–3 kHz) and random-frequency, two-tone complexes. Maskers were presented at an overall level of 50 dB SPL (47 dB/component) for a total duration of 120-ms, including 5-ms, $\cos^2$ onset/offset ramps. The 120-ms masker bursts repeated continuously throughout the testing session with no temporal overlap between successive masker bursts. For the random two-tone masker, frequency components for each 120-ms burst were independently selected from two different uniform distributions. One component was drawn from a range of 0.3–0.92 kHz and the second from a range of 1.08–3 kHz. The 1-kHz signal, when present, was gated simultaneously with one of the repeating 120-ms masker bursts.

Stimuli were generated digitally at a 25-kHz sampling rate using Tucker-Davis Technologies (TDT) system III programmable hardware (RP2) and then low pass filtered at 4 kHz. Signal and masker were attenuated separately (TDT PA5), mixed, fed to a headphone buffer (TDT HB7), and to the left ear of the subject through an insert phone (ER1, Etymotic Research). The presentation of stimuli was controlled by a computer using custom software.

2.3 Procedure

Across four conditions, two experimental variables were manipulated: (1) masker type (noise versus random two-tone) and (2) signal-temporal uncertainty (uncertain versus defined listening interval). Trials were conducted in runs of 20 trials using a single-interval, yes/no procedure. For temporally uncertain conditions, an observer outside the booth initiated each trial. Trials were either "signals", in which the 1-kHz tone was presented simultaneously with one presentation of the repeating masker, or "nonsignals" in which only the masker was presented. When present, the signal coincided with the second masker burst following the observer's initiation of the trial. Subjects were not provided information regarding when an observation interval occurred and were instructed to press ⟨+⟩ on a keyboard whenever they heard the 1-kHz tone. The listening interval ended when the subject indicated a response or after 4 s (maximum of 33 masker bursts). A failure to press ⟨+⟩ during the 4-s listening interval indicated a "no" response. Trial-by-trial feedback was not provided, but subjects were informed of the overall hit and false alarm rate following each run of 20 trials.

An identical procedure was used for temporally defined conditions, except that the subject (rather than the observer outside of the booth) initiated each trial by pressing ⟨enter⟩ on a keyboard. In contrast to Best *et al.* (2007) and Leibold and Werner (2003), visual cues were not used to indicate the listening interval. Instead, the listening interval was predictable and coincided with the second masker burst following the subject's initiation of each trial.

Subjects had at least 2 h of training with the random two-tone masker for both temporal conditions prior to testing. After completing training, data were collected in runs of 20 trials, with signal level fixed within a run. Five fixed signal levels were selected for each subject and condition. The mid-point of the five levels was estimated using a one-up, one-down, single-interval adaptive procedure that tracked the 50% point on the psychometric function (Levitt, 1971). The remaining four signal levels corresponded to −6, −3, +3, and +6 dB around the mid-point. This approach ensured an individualized range of signal levels spanning the dynamic range of the psychometric function for each subject.

For testing, a constant-stimuli procedure with a 0.5 *a priori* probability of signals was used. Subjects were informed of the signal-nonsignal probability. Masker type and temporal condition were fixed within a given block of runs. Five runs were conducted for each block (100 trials total), varying signal level across runs. Testing order for fixed-level runs was counterbalanced across subjects, with subjects completing all conditions for a given masker before changing masker type. For each condition, testing was conducted in a descending order of signal level. The entire sequence was then repeated in an ascending order of signal level, resulting in 40 trials at each of the five signal levels for each condition.

For each subject and condition, values of d' were computed for the five signal levels and used to construct a psychometric function following Dai (1995). This procedure estimates a

Table 1. Individual and mean estimates of threshold (dB SPL), slope ($\log d'/\mathrm{dB}$) and criterion from the individual fitted psychometric functions. Values of r^2 show the proportion of variance in the data accounted for by the estimates.

	Noise masker							
	Uncertain				Defined			
Subject	Threshold	Slope	Criterion	r^2	Threshold	Slope	Criterion	r^2
S1	33.3	0.7	1.0	0.88	34.6	1.3	0.6	0.90
S2	35.5	0.8	0.6	0.92	32.4	0.8	0.7	0.95
S3	34.9	1.1	1.4	0.94	33.8	1.0	1.1	0.90
S4	34.6	0.9	1.5	0.83	30.0	0.5	1.0	0.98
Mean	34.6	0.9	1.1	0.89	32.7	0.9	0.9	0.93
	Random two-tone masker							
S1	47.5	0.4	0.1	0.67	32.2	0.3	0.3	0.57
S2	17.2	0.2	0.6	0.51	5.2	0.2	0.8	0.86
S3	18.3	0.3	0.8	0.77	13.3	0.4	0.6	0.54
S4	30.3	0.2	0.5	0.58	25.3	0.6	0.2	0.76
Mean	28.3	0.3	0.5	0.63	19.0	0.4	0.5	0.68

threshold corresponding to $d'=1$. Psychometric functions were fitted based on 200 trials, with 40 trials per signal level. All fitted psychometric functions demonstrated an r^2 of >0.5.

3. Results and discussion

Threshold, slope, criterion, and r^2 estimates are provided in Table 1. Thresholds for the noise masker were uniform across subjects and temporal conditions, ranging from 33.3 to 35.5 dB SPL for the temporally uncertain condition and from 30.0 to 34.6 dB SPL for the temporally defined condition. Thresholds were more variable for the random two-tone masker, ranging from 17.2 to 47.5 dB SPL for the temporally uncertain condition and from 5.2 to 32.2 dB SPL for the temporally defined condition.

Figure 1 presents the amount of masking release associated with defining the listening interval (temporally uncertain minus temporally defined threshold) for each subject and for the average across subjects. Data for the noise and random two-tone masker are shown by open circles and filled squares, respectively. The average effect of signal-temporal uncertainty on detection for a 1-kHz tone in the presence of a continuous sequence of noise bursts was 2 dB. This result is similar to previously reported estimates (e.g., Watson and Nichols, 1976; Green and Weber, 1980), confirming that signal-temporal uncertainty has a minimal effect on pure-tone detection in noise. In contrast to the results for the noise masker, the average effect of signal-temporal uncertainty for the random two-tone masker was 9 dB.

A one-way repeated-measures analysis of variance (ANOVA) on threshold was performed for each masker type. Thresholds were significantly higher for the temporally uncertain versus the temporally defined condition for the random two-tone masker [$F(1,3)=12.9$; $p=0.04$], but were not significantly different for the noise masker [$F(1,3)=2.4$; $p=0.2$]. These findings are consistent with the hypothesis that the effect of signal-temporal uncertainty is greater for stimuli that generate substantial informational masking than for stimuli that generate little or no informational masking.

As shown in Table 1, subjects' psychometric functions tended to have a shallower slope for the random two-tone compared to the noise conditions. This observation is consistent with previous work (e.g., Lutfi *et al.*, 2003). Note, however, that no systematic differences in slope were observed across temporally uncertain and temporally defined conditions for either masker in the current study.

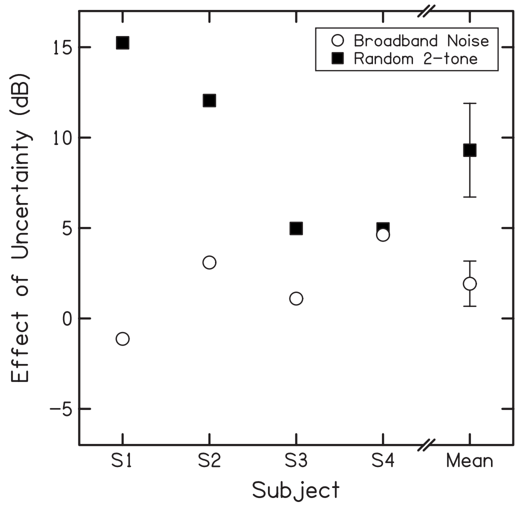

Fig. 1. The release from masking produced by reducing signal-temporal uncertainty (temporally uncertain minus temporally defined threshold) is plotted for individual subjects and for the mean across subjects. Error bars indicate ±1 standard error of the mean across subjects. Masking release for the broadband noise masker is shown by open circles. Masking release for the random two-tone masker is shown by filled squares.

As previously reported (e.g., Neff and Dethlefs, 1995), individual differences in performance were large for both random two-tone masker conditions. Estimates of the standard error for thresholds averaged across subjects for the random two-tone masker were 7.0 and 6.0 dB for temporally uncertain and temporally defined conditions, respectively. In sharp contrast, estimates of the standard error were 0.4 and 1.0 dB for temporally uncertain and temporally defined conditions, respectively. Moreover, psychometric functions fitted to the noise data accounted for a greater proportion of variance than psychometric functions fitted to the random two-tone data. As shown in Table 1, values of r^2 for the noise masker ranged from 0.83 to 0.94 when the listening interval was uncertain and from 0.90 to 0.98 when the listening interval was defined. In contrast, values of r^2 for the random two-tone masker ranged from 0.51 to 0.77 when the listening interval was uncertain and from 0.54 to 0.86 when the listening interval was defined. Thus, both between-subjects and within-subjects variability appear to be greater for the random two-tone masker relative to the noise masker.

The results of Best *et al.* (2007) support the idea that the effect of signal-temporal uncertainty is greater for conditions expected to produce substantial informational masking. Best *et al.* found that the benefit of knowing when to listen was larger for identifying birdsong than for recalling digits embedded in either forward or reverse speech. The authors suggested that this discrepancy may reflect differences in target-masker similarity across conditions. The current results for the random two-tone masker are in agreement with this suggestion. Both the target and masker stimuli were comprised of pure tones, presumably resulting in high target-masker similarity. A related explanation is that the current results reflect a combined effect of signal-temporal and masker-spectral uncertainty. Future work examining performance across multi-tonal maskers with random and fixed spectra might provide insight into the contributions of both uncertainty and similarity for these stimuli and conditions.

This study was based on that of Leibold and Werner (2003), which found an average effect of signal-temporal uncertainty of 16 dB using similar stimuli, but used a single-interval, adaptive procedure. Consistent with the earlier study, the current results indicate a larger effect of signal-temporal uncertainty on detection for a 1-kHz tone in the presence of a random two-tone masker than has been observed for tone-in-noise detection (e.g., Green and Weber, 1980). However, the average effect of signal-temporal uncertainty for the random two-tone masker was reduced in the current study (9 dB) compared to the previous work (16 dB). This discrepancy might reflect individual differences. Note that a 15-dB effect was observed for one of the four subjects in the current study, similar to the average effect reported by Leibold and Werner. Alternatively, differences in response bias across temporally uncertain and temporally defined conditions may have contributed to the larger effect observed by Leibold and Werner. Researchers have noted that subjects may adopt a conservative bias for single-interval tasks (e.g., Marshall and Jesteadt, 1986). The influence of this conservative bias on pure-tone thresholds in quiet, however, appears to be small (e.g., Swets *et al.*, 1961; Marshall and Jesteadt, 1986). To examine whether the effect of response bias was larger for the current multi-tonal stimuli, individual estimates of criterion were calculated. As shown in Table 1, subjects appeared to be more conservative listeners in the current study compared to Leibold and Werner (2003). For the random two-tone masker, the criterion estimates ranged from 0.1 to 0.8 for the temporally uncertain condition and from 0.2 to 0.8 for the temporally defined condition. In contrast, Leibold and Werner observed a range of −1.4 to 0.8 for the adaptive temporally uncertain condition and −0.5 to 0.3 for the adaptive temporally defined condition. Further investigation is required to determine whether the apparent increase in criterion effects extends to other stimuli and procedures used to study informational masking.

In summary, this study examined whether the effect of signal-temporal uncertainty was larger for a masker expected to produce substantial informational masking than for a masker expected to produce minimal informational masking. The results confirm those of previous studies (e.g., Green and Weber, 1980), indicating a 2-dB effect of signal-temporal uncertainty for tone-in-noise detection. As predicted, the effect of signal-temporal uncertainty was significantly greater for the random two-tone masker, with effects ranging from 5 to 15 dB across subjects. These results are consistent with the hypothesis that the effect of signal-temporal uncertainty is higher for conditions in which baseline informational masking is high.

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References and links

Best, V., Ozmeral, E. J., and Shinn-Cunningham, B. G. (**2007**). “Visually-guided attention enhances target identification in a complex auditory scene,” J. Assoc. Res. Otolaryngol. **8**, 294–304.

Chang, P., and Viemeister, N. F. (**1991**). “Temporal windows for signals presented at uncertain times,” J. Acoust. Soc. Am. **90**, 2248.

Dai, H. (**1995**). “On measuring psychometric functions: A comparison between the adaptive up-down and constant-stimulus method,” J. Acoust. Soc. Am. **98**, 3135–3139.

Durlach, N. I. (**2006**). “Auditory masking: Need for improved conceptual structure,” J. Acoust. Soc. Am. **120**, 1787–1790.

Durlach, N. I., Mason, C. R., Kidd, G., Arbogast, T. L., Colburn, H. S., and Shinn-Cunningham, B. G. (**2003**). “Note on informational masking,” J. Acoust. Soc. Am. **113**, 2984–2987.

Egan, J. P., Greenberg, G. Z., and Schulman, A. I. (**1961**). “Interval of time uncertainty in auditory detection,” J. Acoust. Soc. Am. **33**, 771–778.

Green, D. M., and Weber, D. L. (**1980**). “Detection of temporally uncertain signals,” J. Acoust. Soc. Am. **67**, 1304–1311.

Jones, M. R., and Yee, W. (**1993**). “Attending to auditory events: the role of temporal organization,” in *Thinking in Sound: The Cognitive Psychology of Human Audition*, edited by S. McAdams and E. Bigand (Oxford U. P., Oxford).

Kidd, G., Jr., Mason, C. R., Deliwala, P. S., Woods, W. S., and Colbun, H. S. (**1994**). “Reducing informational masking by sound segregation,” J. Acoust. Soc. Am. **95**, 3475–3480.

Leibold, L. J., and Werner, L. A. (**2003**). “Infants’ detection in the presence of masker uncertainty,” J. Acoust. Soc. Am. **113**, 2208.

Leibold, L. J., and Werner, L. A. (**2006**). “Effect of masker-frequency variability on the detection performance of infants and adults,” J. Acoust. Soc. Am. **119**, 3960–3970.

Levitt, H. (**1971**). “Transformed up-down methods in psychoacoustics,” J. Acoust. Soc. Am. **49**, 467–477.

Lutfi, R. A., Kistler, D. J., Callahan, M. R., and Wightman, F. L. (**2003**). “Psychometric functions for informational masking,” J. Acoust. Soc. Am. **114**, 3273–3282.

Marshall, L., and Jesteadt, W. (**1986**). “Comparison of pure-tone audibility thresholds obtained with audiological and two-interval forced-choice procedures,” J. Speech Hear. Res. **29**, 82–91.

Neff, D. L., and Dethlefs, T. M. (**1995**). "Individual differences in simultaneous masking with random-frequency, multicomponent maskers," J. Acoust. Soc. Am. **98**, 135–134.

Neff, D. L., and Green, D. M. (**1987**). "Masking produced by spectral uncertainty with multicomponent maskers," Percept. Psychophys. **41**, 409–415.

Swets, J. A., Tanner, W. P., and Birdsall, T. G. (**1961**). "Decision processes in perception," Psychol. Rev. **68**, 301–340.

Watson, C. S., and Nichols, T. J. (**1976**). "Detectability of auditory signals presented without defined observation intervals," J. Acoust. Soc. Am. **59**, 655–668.